AMERICAN Journal of Engineering,
Mechanics and Architecture
Volume 3, Issue 4, 2025 ISSN (E): 2993-2637

Finite Element Modelling for RC Portal Frames Strengthened by CFRP Composites by Using EBR, NSM, EBROG and EBRIG Techniques

Jaafar D. Witwit
Department of computer science, Alsafwa University College, Karbala Governorate, Iraq

Abstract: This research studied many types of concrete strengthening by using CFRP-sheet and CFRP-bar. Finite element modelling was created by using Abaqus 6.14 program. The control frame was calibrated with an experimental specimen, which tested under 2-points load up to failure. Model verification including ultimate load, maximum mid span deflection, mode failure. Model Convergence study was studied. Numerical results showed that using CFRP- sheet increasing ultimate load about (25%) compared with the control specimen. However, Using EBROG and EBRIG techniques increasing ultimate load about (4.7 %, 28.50 %) respectively. Strengthening frame with one and two CFRP bars increasing ultimate load about (38.8%, 20.47 %) respectively. On the other hand, Frame reinforced with two and three CFRP bars (without steel reinforcement) increased ultimate load about (3.60 %, 18.25 %).

Keywords: Portal frame, CFRP, EBROG, EBRIG, NSM, Abaqus/CAE.

INTRODUCTION

In the past two decades, using FRP composites in RC structures have gained a worldwide, because it gives high tensile strength, ease in application and light weight material. At many members FRP is the only material can be used in strengthened especially when machinery cannot gain access [1][2].

There are many types of FRP composites, such as carbon, glass and aramid. Almost 95 percent of all applications for structural strengthening in civil engineering are by carbon fibers which is symbolled CFRP [3].

The common method to apply FRP on concrete is externally bonded reinforcement (EBR). This method resulted in undesirable failure which is debonding failure. Debonding failure occurs before reaching to the ultimate tensile strength of FRP in addition it is a brittle failure [4]. A new technique was applied to prevent debonding failure in FRP strengthening, this method is near surface mounted (NSM) [5]. This method created a groove in concrete and insert CFRP bar or strip inside to increase flexural strength of concrete [6]. But this method not applicable with sheets, so other techniques were appeared which are externally bonded reinforcement on grooves (EBROG). EBROG technique has been recently introduced by Mostofinejad & Mahmoudabadi [7]. At 2013 Mostofinejad and Shameli combined the effect of NSM and EBROG to achieved a new technique called externally bonded reinforcement in grooves (EBRIG) [8]. This technique prevents debonding failure and achieve FRP rupture in flexural strength of beam [9]. Both techniques consist of cutting grooves into bottom of beam (tension face) and filling them by epoxy resin. After that, apply FRP sheets. When FRP applied out the groove then the technique called EBROG, otherwise, (i.e., applied inside the grooves) it will called EBRIG [10]. These methods have developed and evaluated to install FRP composite used for strengthening beams [11], slabs [9],[12] and columns [13] [14] and increasing both tensile and shear strength. Figure. 1 showed EBR, NSM, EBROG, EBRIG strengthening methods.

The present study aims to investigate the frame behavior strengthened by CFRP sheets and rebars. Many types of strengthening were investigated, EBR NSM, EBROG and EBRIG. EBR, EBROG and EBRIG techniques were used for CFRP sheet, However NSM technique was used for CFRP rebar. In addition, investigated the concrete frame behavior reinforced by CFRP rebar without steel reinforcement was done. Types of strengthening were consisted of beam strengthening at bottom face, top face (negative moment region) and Columns strengthening at tension face.

Strengthening techniques were shown in Figure. 1

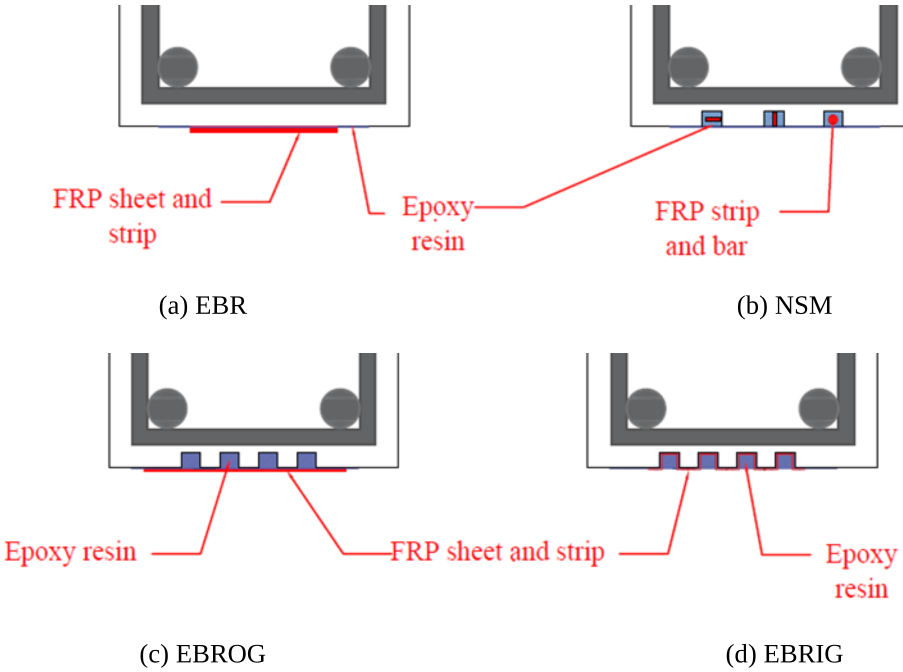


Figure. 1: EBR, NSM, EBROG and EBRIG Methods [15], [16]

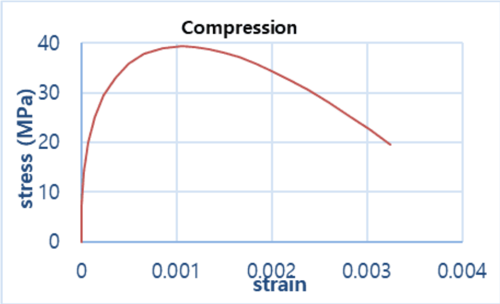
Finite Element Modelling Methodology

2.1 Material modelling

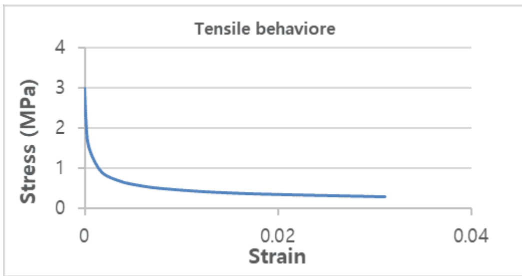
A full model was created by using Abaqus 6.14 program to simulate behavior of reinforced concrete portal frame [17], [18]. Considered concrete material modelling was concrete damage plasticity (CDP). Elastic and plastic properties for concrete material was listed in Table 1 below. Concrete compression and tension behavior were shown in Figure 2 (a,b,c and d). On the other hand, steel reinforcement material modelling was listed in Table 2 . Finally, CFRP material modelling was shown in Table 4.

Table 1: Concrete elastic properties

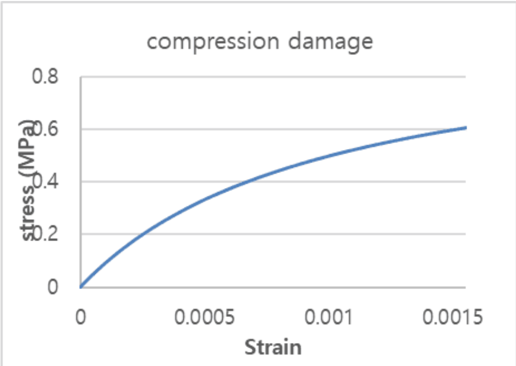
Parameter	Density (tonne/mm^3)	Modulase of Elasticity, E (Mpa)	Poisson ratio	Dialation angle	Eccentricity	fbo/fco	K	Viscosity parameter
Value	24000	33195	0.15	25	0.1	1.16	0.667	0



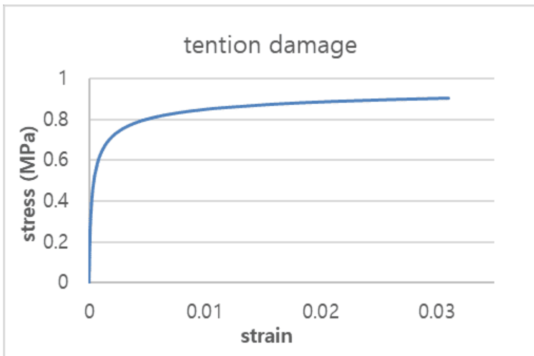
(a) Concrete compression behavior



(b) Concrete tensile behavior



(c) concrete compression damage



(d) concrete tension damage

Figure 2: Modeled concrete material behavior

Table 2: Steel reinforcement properties

Properties	Flexural reinforcement	Shear reinforcement
As (mm2)	112	48.64
Modulus of elasticity, E (MPa)	215507	215507
Poison's ratio (ν)	0.3	0.3
Yield strength, Fy (MPa)	367.9	367.9
Ultimate strength, Fu (MPa)	647.3	647.3

__2.2__ CFRP and adhesive epoxy material modelling

The Common model in Abaqus/CAE is Hashin's model [19] for orthotropic laminar material. CFRP sheets were modeled by using this model with properties as listed in Table 3 below. Hashin's model considered four mode of failure criteria: fiber tension, and compression, matrix tension and compression [6][20]. CFRP properties for both sheet and rebar as reported by the manufacturer were listed Table 4 below. Both CFRP sheets rebar were assumed to have a linear elastic behavior with brittle failure where the CFRP reaching the tensile strength [6].

Table 3: CFRP sheet model by using hashin's model

E1	E2	Nu	G12	G13	G23	Xt	Xc	Yt	Yc	Sx	Sy
234000	10300	0.28	7170	7170	6300	4300	1700	60	40	130	130

Where:

E1, E2 is longitudinal and transverse modulus of elasticity respectively.

Nu: poison's ratio.

G12, G13 and G23: shear modulus of elasticity in 1-2,1-3 and 2-3 plane.

Xt, Xc: longitudinal tensile strength and compression strength.

Yt, Yc: transverse tensile strength and compression strength.

Sx, Sy: in-plane shear strength.

The adhesive was modeled as an isotropic material with linear elastic behavior. The elastic modulus and tensile strength for epoxy resin Sikadur C300, were 3.8 GPa and 30 MPa respectively as reported by the manufacturer [21]. On the other hand, for epoxy resin Sikadur C31, were equal to 10 GPa and 85 MPa respectively [22].

2.3 *Interaction*

The interaction of concrete with steel reinforcement and CFRP bars was modeled by using embedded region. With this model rebars will be embedded in concrete in away that they will both have the same degrees of freedom [6]. On the other hand, interaction between concrete and CFRP sheet was modeled by using tie constraint. With this type of model (tie constraint), the members remain attached together throughout analysis [6].

Table 4: Technical properties of CFRP Composites [23], [24].

Properties	Sika Warp® Sheet Hex-230C	Aslan 201 Rebar
Tensile strength (MPa)	4300	2068
Modulus of elasticity, E (GPa)	234	124
Elongation at break (%)	1.8	1.7
Width (mm)	60	-
Thickness (mm)	0.131	-
Diameter (mm)	-	6.4
Cross sectional area, A (mm2)	-	31.67
Ultimate strain	-	0.017

2.4 Boundary conditions

Boundary conditions for frames were constraint at bottom of both columns in directions x,y and z (i.e. ux= uy= uz= 0) as shown in Figure 3 below.

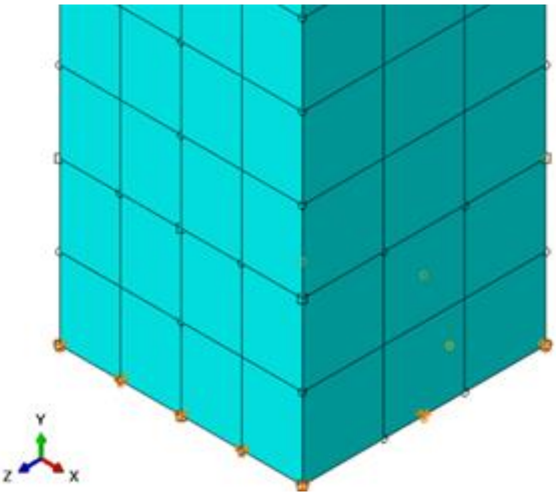


Figure 3: Boundary condition for modeled frames

2.5 Applied load and Steps

Total force applied on steel plate was 300 kN distributed uniformly on the plates. Also, load steps were 300 steps with initial load step 0.01 Maximum increasing step 25 and minimum 0.001

2.6 Used element

Used elements for model were the cubic element C3D8R with eight nodes and three degrees of freedom per node and reduced integration for concrete and adhesive. Element T3D2 was used for modelling the flexural, transverse reinforcements and CFRP bars, while CFRP sheet was modeled using the shell element S4R with four nodes and reduced integration. Types of used elements were listed in Table 5 below.

Table 5: Types of used elements [25], [17]

Modeled material	Element Type	Element symbol
Concrete material and Adhesive Material	Cubic element with eight nodes and three degrees of freedom per node and reduced integration	C3D8R
Flexural and shear reinforcement	linear truss element	T3D2
Load plates	Cubic element with eight nodes and three degrees of freedom per node	C3D8
CFRP- sheet	shell element with four nodes, reduced integration	S4R
CFRP-bar	linear truss element with four nodes and reduced integration	T3D2

2.7 Calibration and Convergence study

The model was calibrated with an experimental control specimen [26] and the ultimate load difference between them was (5%) as listed in Table 6. In addition, crack patterns comparison between the finite element model with an experimental specimen were done, as shown in Figure4.

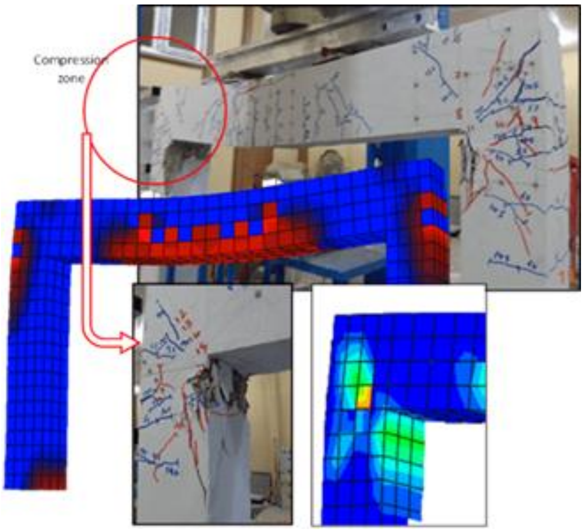


Figure 4: Crack pattern comparison between experimental test and Numerical model

Table 6: Calibration with experimental specimen

	Experimental	F.E.M. model	Tolerance (%)
Ultimate load, (kN)	176.00	185.51	5%
Maximum mid span deflection, (mm)	13.08	15.60	19%

A convergence study was carried out to conducting a sensitivity analysis on mesh size by decreasing it. When the decreasing mesh size was no significant improvement in the results, then mesh size was chosen. Adopted mesh size was (25 mm) with number of elements (6710) as shown in Figure 5.

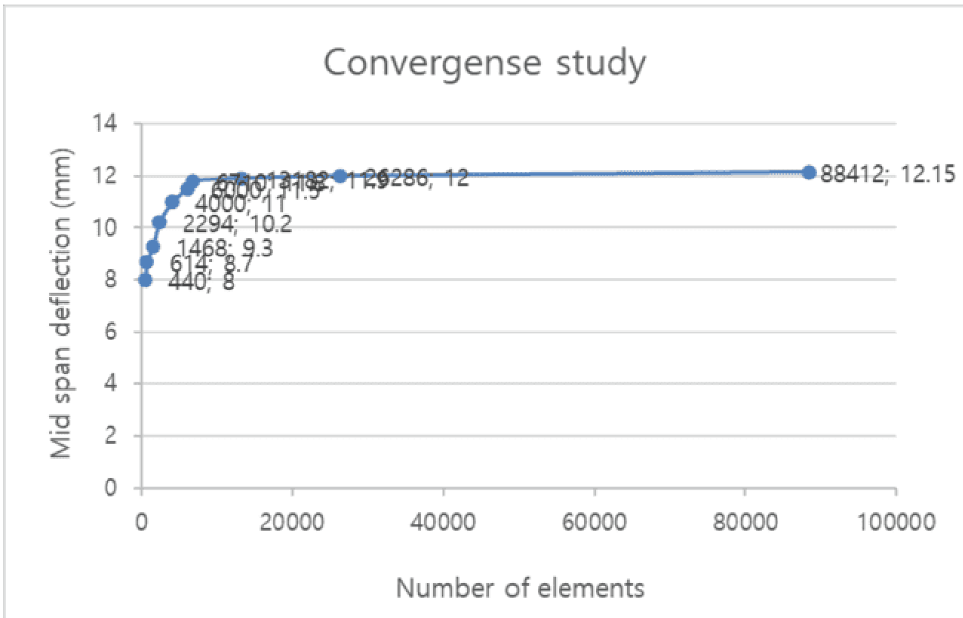


Figure 5: Convergence study

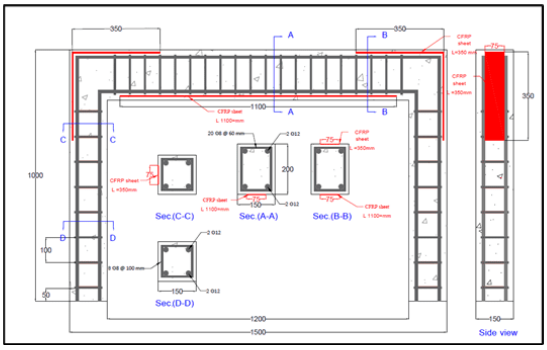
2.8 Specimens Symbol

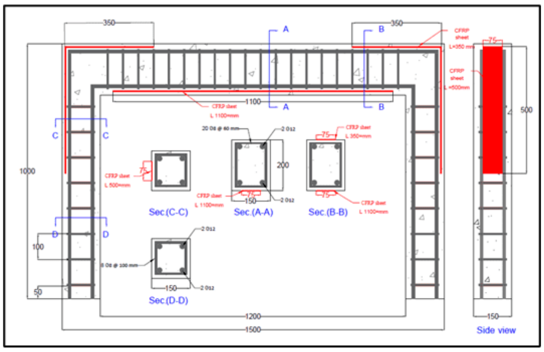
Specimens' symbols were listed in Table 7 below. The reinforcements and strengthened modes were shown in Figure 6 below. Group A contained frames strengthened with CFRP sheet, while group B contained frames strengthened by CFRP bar and group C contained frames reinforced with CFRP bar without steel reinforcement.

Table 7: Specimens Symbol

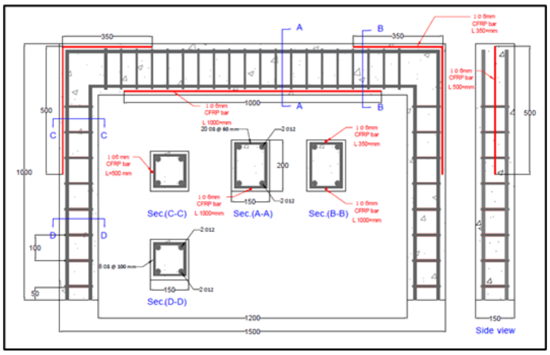
No.	Group	Symbol	Description
1.		Fco-e	Control frame (Experimentally tested)
2.		Fco-n	Control frame (Numerical modeled)
3.	Group A	FS-350	Frame strengthened with CFRP-Sheet with length 350 mm
4.		FS-500	Frame strengthened with CFRP-Sheet with length 500 mm
5.		FSO-500	Frame strengthened with CFRP-Sheet out of groove at beam bottom and columns with length 500 mm
6.		FSI-500	Frame strengthened with CFRP-Sheet in groove at beam bottom and columns with length 500 mm
7.	Group B	FB1-500	Frame strengthened with one CFRP-Bar with length 500 mm
8.		FB1D-500	Frame strengthened with one CFRP-Bar with length 500 mm and diagonal rebar with length 250 mm [27]
9.		FB2-500	Frame strengthened with two CFRP-Bar with length 500 mm

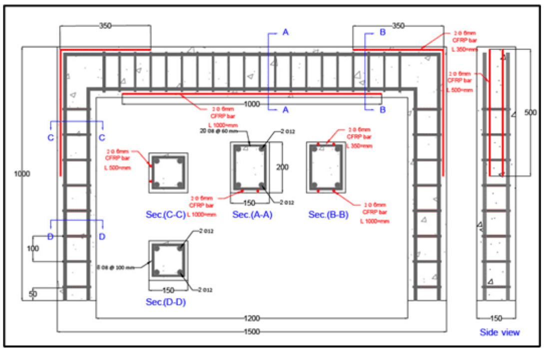
10.	Group C	FBr2	Frame Reinforced with two CFRP-Bars
11.		FBr3	Frame Reinforced with three CFRP-Bar at beam bottom and two at top and columns





(e) FS-350 (f) FS-500, FSO-500, FSI-500





(g) FB1-500 (h) FB2-500, FBr2-500

Figure 6: Frame reinforcement and Strengthening modes

Results and discussion

3.1 Load-Deflection Curves

Load deflection curves for investigated frames were shown in Figure 7.

Results summary for ultimate load, deflection at mid span and equivalent deflection at mid span compared with control frame were Shown in Table 8.

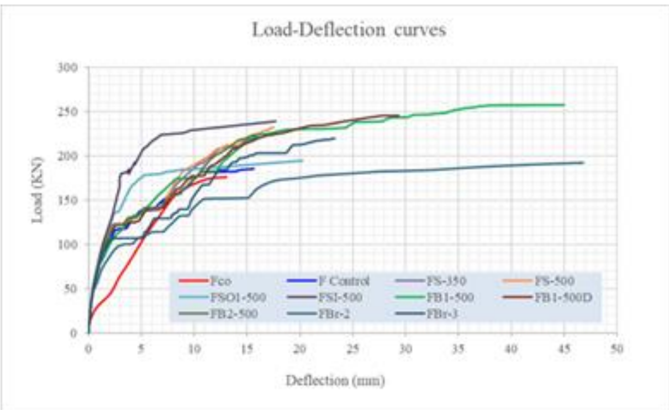


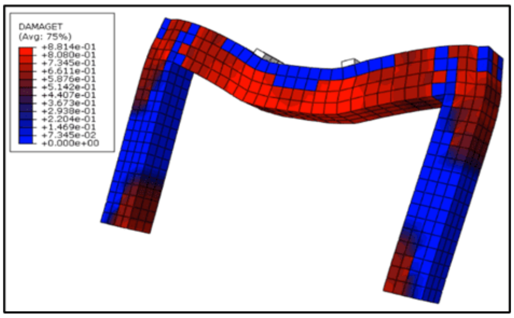
Figure 7: Load-deflection Curves for investigated frames

Table 8: Results summary for modeled frames

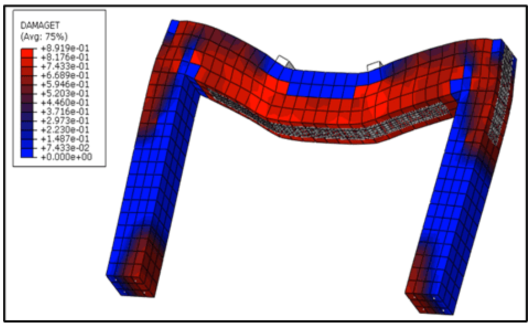
No.	Symbol	Ultimate Load (kN)	% Increasing in ultimate load compared to control frame	Max. deflection at mid span of beam (mm)	% Decreasing in Max. deflection compared to control frame	Equivelant deflection (at 185 kN)	% Decreasing in equivalent deflection (at 185 kN)
1	Fco-e	176.00	-	13.08	-	-	-
2	Fco-n	185.51	5.40	15.60	19.25	-	-
3	FS-350	220.35	18.78	16.10	3.26	9.74	-37.58
4	FS-500	231.86	24.99	23.65	51.67	9.38	-39.86
5	FSO-500	194.24	4.71	9.75	-37.47	11.16	-28.44
6	FSI-500	238.38	28.50	9.73	-37.64	4.09	-73.78
7	FB1-500	257.48	38.80	44.99	188.45	12.26	-21.38
8	FB1D-500	244.91	32.02	29.32	87.98	11.38	-27.02
9	FB2-500	223.48	20.47	15.75	0.96	10.82	-30.66
10	FBr-2	192.18	3.60	46.78	199.96	34.45	120.85
11	FBr3	219.36	18.25	23.26	49.14	13.13	-15.83

3.2 Crack Patterns (tension Damage)) for modeled frames

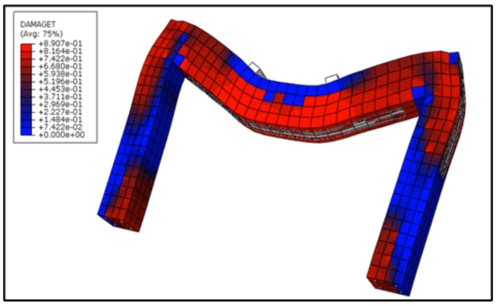
A tension and compression crack patterns for tested frame were shown in Figure 8 and Figure 9 respectively with a scale factor 10.

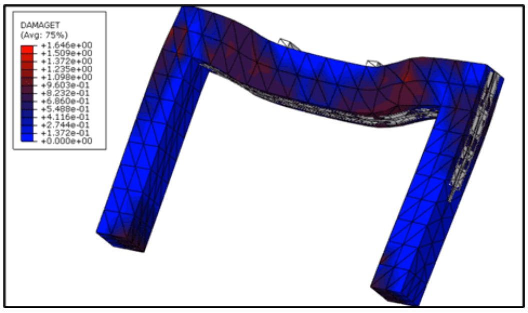


(a) FCo-n



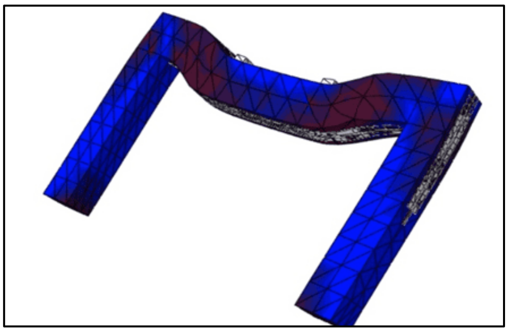
(b) FS-350

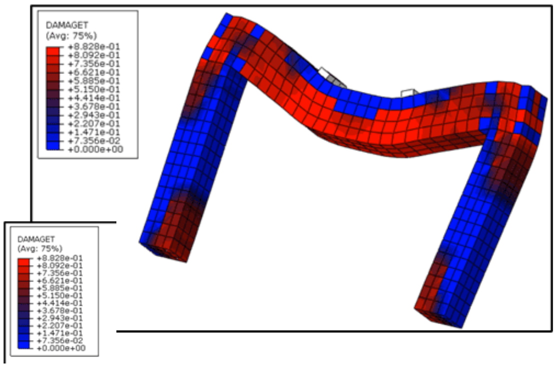




(c) FS-500

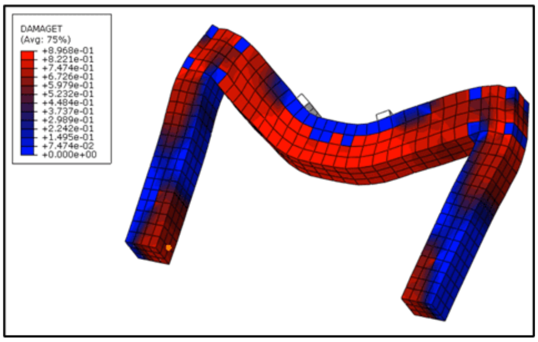
(d) FSO-500

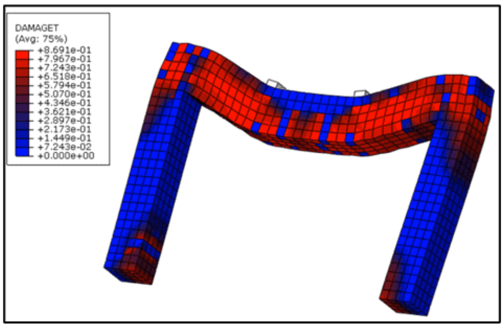




(e) FSI-500

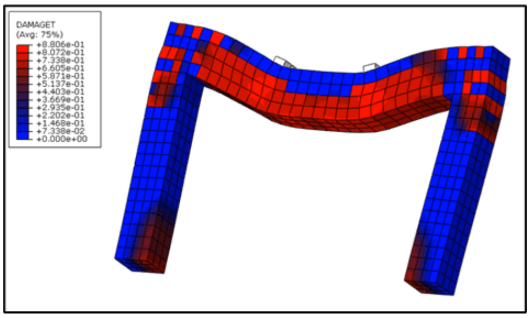
(f) FB1-500

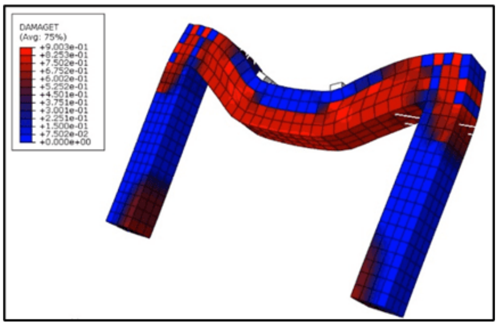




(g) FB1D-500

(h) FB2-500



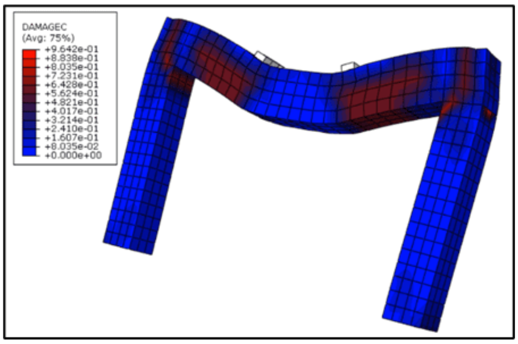


(i) FBr-2

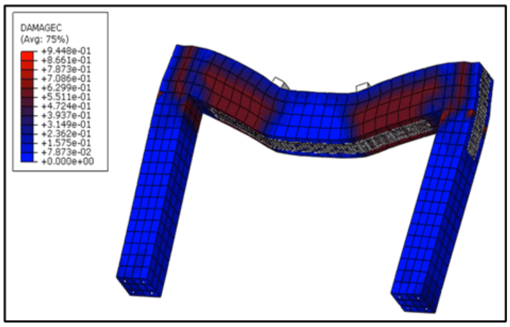
(j) FBr-3

Figure 8: Crack Patterns (tension Damage) for modeled frames

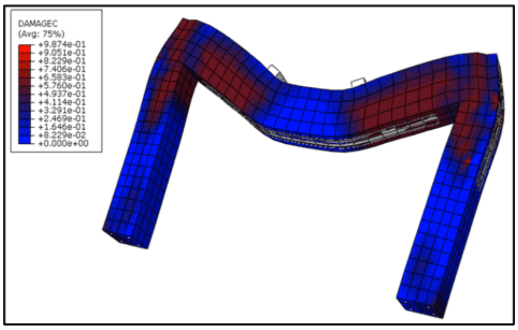
3.3 Crack patterns (compression damage) for modeled frames



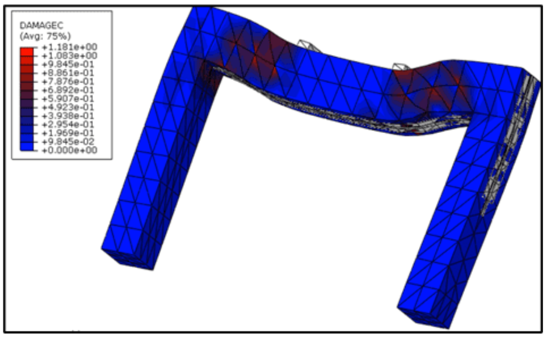
(a) FCo-n



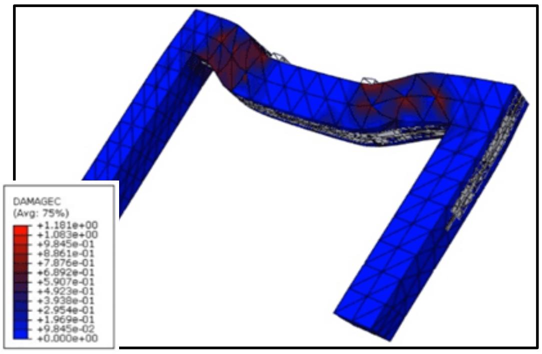
(b) FS-350



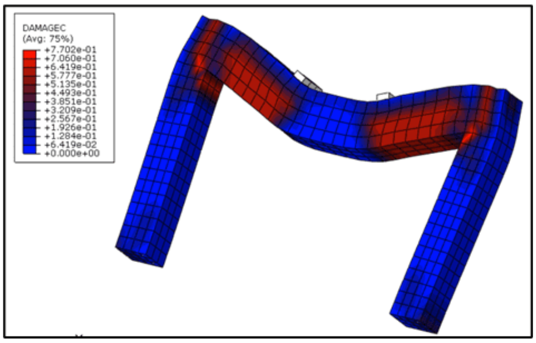
(c) FS-500



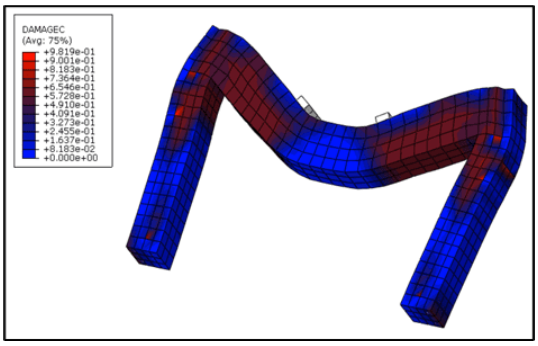
(d) FSO-500



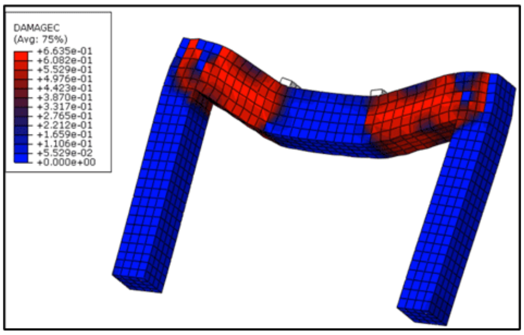
(e) FSI-500



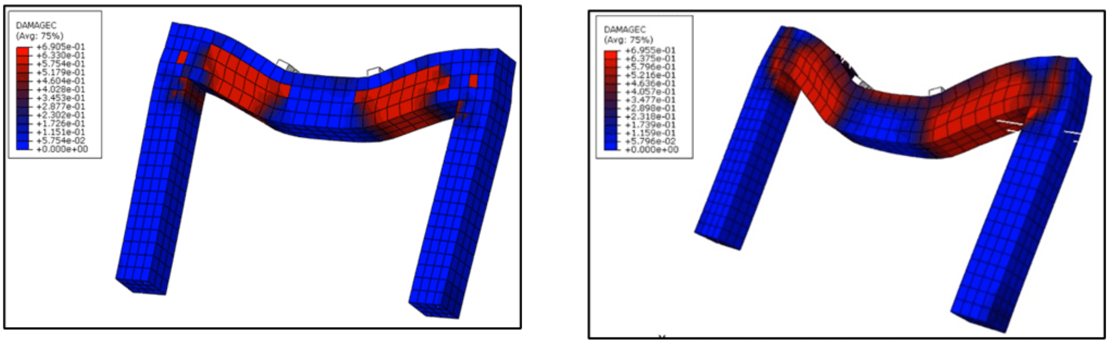
(f) FB1-500



(g) FB1D-500



(h) FB2-500



(i) FBr-2 (j) FBr-3

Figure 9: Crack Patterns (compression Damage) for modeled frames

3.4 Results comparison

An ultimate load comparison between investigated frame were listed in Table 9 to obtain the best types for strengthening.

Table 9: An ultimate load comparison between different types of strengthening

			1	2	3	4	5	6	7	8	9	10	11
			Fco-e	Fco-n	FS-350	FS-500	FSO-500	FSI-500	FB1-500	FB1D-500	FB2-500	FBr-2	FBr3
			176.00	185.51	220.35	231.86	194.24	238.38	257.48	244.91	223.48	192.18	219.36
1	Fco-e	176.00	-	5.40									
2	Fco-n	185.51	5.40		18.78	33.18	-0.58	21.14	38.80	32.02	20.47	3.60	18.25
3	FS-350	220.35		18.78		12.13	-16.30	1.99	16.85	11.15	1.42	-12.78	-0.45
4	FS-500	231.86		24.99	5.23		-16.23	2.81	11.05	5.63	-3.62	-17.11	-5.39
5	FSO-500	194.24		4.71	-11.85	-16.23		22.72	32.56	26.09	15.05	-1.06	12.93
6	FSI-500	238.38		28.50	8.18	2.81	22.72		14.58	8.98	-0.56	-19.38	12.93
7	FB1-500	257.48		38.80	16.85	11.05	32.56	8.01		-4.88	-13.21	-25.36	-7.98
8	FB1D-500	244.91		32.02	11.15	5.63	26.09	2.74	-4.88		-8.75	-21.53	-10.43
9	FB2-500	223.48		20.47	1.42	-3.62	15.05	-6.25	-13.21	-8.75		-14.00	-1.84
10	FBr-2	192.18		3.60	-12.78	-17.11	-1.06	-19.38	-25.36	-21.53	-14.00		14.14
11	FBr3	219.36		18.25	-0.45	-5.39	12.93	-7.98	-14.80	-10.43	-1.84	14.14	

Conclusions

From Figure 8,Figure 9, Table 8 and Table 9 we can concluded that:

1. Finite element model gives a good result compared to experimental test with error about (5.4 %) resulted in ultimate load compression.
2. Strengthening frame with CFRP sheet with length (350, 500) mm increasing ultimate load about (18.7%, 25 %) respectively and decreasing equivalent deflection about (37.58%,39%) respectively.

3. Using EBROG and EBRIG techniques increasing ultimate load about (4.7 %, 28.50 %) respectively and decreasing equivalent deflection about (28.44 %, 73.78 %) respectively
4. Strengthening frame with one and two CFRP bars increasing ultimate load about (38.8%, 20.47 %) respectively and decreasing equivalent deflection about (21.38 %, 30.66 %) respectively.
5. Increasing CFRP length from 350 mm to 500 mm at columns increasing ultimate load only about (5.23%).
6. Frame reinforced with two and three CFRP bars (without steel reinforcement) increased ultimate load about (3.60 %, 18.25 %). On the other hand deflection for frame reinforced with two bars increased about 120.85% while frame with three bars decreased about 15.83%.
7. Using Diagonal strengthening in CFRP bar not increasing strength noticeably.

REFERENCES

1. Mostofinejad, Davood and Shameli, Seyed and Hosseini, Ardalan, (2012), "Experimental Study on the Effectiveness of EBROG Method for Flexural Strengthening of RC Beams", The 6th International Conference on FRP Composites in Civil Engineering, CICE 2012, June.
2. Hosseini, Ardalan and Mostofinejad, Davood , (2013), "Experimental Evaluation of FRP-to-Concrete Bond Strength in EBROG Technique for Strengthening Concrete Members", 2nd Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, SMAR, turkey,.
3. Nordin, H., (2003) "Flexural Strengthening of Concrete Structures with Prestressed Near Surface Mounted CFRP Rods", Licentiate Thesis, Lulea University of Technology, Lulea, Sweden.
4. Teng, J.G. and et. al. (2006), "Debonding Failures of RC Beams Strengthened with Near Surface Mounted CFRP Strips". " Journal of Composites for Construction - J COMPOS CONSTR". 10. https://doi.org/10.1061/(ASCE)1090-0268(2006)10:2(92)
5. Galati, Donatella and De Lorenzis, Laura. (2009). "Effect of Construction Details on the Bond Performance of NSM FRP Bars in Concrete". Advances in Structural Engineering. 12. https://doi.org/10.1260/136943309789867836
6. Ehsan Noroozieh · Ali Mansouri, (2019), "Lateral strength and ductility of reinforced concrete columns strengthened with NSM FRP rebars and FRP jacket", International Journal of Advanced Structural Engineering, 11(2), p.p. 195-209. https://doi.org/10.1007/s40091-019-0225-5
7. Mostofinejad, D, Mahmoudabadi, E. (2010). "Grooving as alternative method of surface preparation to postpone debonding of FRP laminates in concrete beams". Journal of Composites for Construction - J COMPOS CONSTR, ASCE, 14: p.p. 804-811. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000117
8. Mostofinejad D, Shameli SM., (2013), "Externally bonded reinforcement in grooves (EBRIG) technique to postpone debonding of FRP sheets in strengthened concrete beams". Construction and Building Materials,38, p.p.751–758.
9. Amiri, S. and Talaeitaba, S., (2020), "Punching shear strengthening of flat slabs with EBROG and EBRIG – FRP strips", Structures, 26, p.p. 139–155. https://doi.org/10.1016/j.istruc.2020.04.017
10. Mostofinejad, Davood and Shameli, Seyed and Hosseini, Ardalan. (2014), "EBROG and EBRIG methods for strengthening of RC beams by FRP sheets". European Journal of Environmental and Civil Engineering. https://doi.org/10.1080/19648189.2014.900523

11. Azizi, R., and Talaeitaba, S.B., (2019), "Punching shear strengthening of flat slabs with CFRP on grooves (EBROG) and external rebars sticking in grooves", International Journal of Advanced Structural Engineering, 11, 79–95 . https://doi.org/10.1007/s40091-019-0218-4

12. Ala Torabian, Brisid Isufi, Davood Mostofinejad, António Pinho Ramos, (2020), "Flexural strengthening of flat slabs with FRP composites using EBR and EBROG methods", Engineering Structures, 211(110483), https://doi.org/10.1016/j.engstruct.2020.110483

13. Khaled Sanginabadi, Azad Yazdani, Davood Mostofinejad, Christoph Czaderski, (2022), "RC members externally strengthened with FRP composites by grooving methods including EBROG and EBRIG: A state-of-the-art review", Construction and Building Materials, 324 (126662). https://doi.org/10.1016/j.conbuildmat.2022.126662

14. Moshiri, N. and et. al. Experimental and analytical study on CFRP strips-to-concrete bonded joints using EBROG method, Composites Part B: Engineering, Volume 158, 2019, Pages 437-447, https://doi.org/10.1016/j.compositesb.2018.09.046

15. Kotynia, Renata. (2011). "Bond between FRP and concrete in reinforced concrete beams strengthened with near surface mounted and externally bonded reinforcement". Construction and Building Materials - CONSTR BUILD MATER. 32. https://doi.org/10.1016/j.conbuildmat.2010.11.104

16. De Lorenzis, Laura & Teng, J.G.. (2007). "Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures", Composites Part B: Engineering, 38, p.p. 119-143. https://doi.org/10.1016/j.compositesb.2006.08.003

17. ABAQUS Inc. (2013) ABAQUS/theory user manual, Version 6.13

18. Smith, Michael., "ABAQUS/Standard User's Manual", Version 6.9.

19. Hashin Z (1980) "Failure criteria for unidirectional fiber composites". J Appl Mech, 47(2):, p.p. 329–334. https ://doi.org/10.1115/1.31536 64

20. Wang, GD., Melly, S.K., (2018), "Three-dimensional finite element modeling of drilling CFRP composites using Abaqus/CAE: a review". Int J Adv Manuf Technol, 94, p.p. 599–614. https://doi.org/10.1007/s00170-017-0754-7

21. Sika (2005), "Sikadur 330-Two Part Epoxy Impregnation Resin ", Technical Data Sheet, Edition 2.

22. Sika, "Sikadur 30-Adhesive for Bonding Reinforcement", Technical Data Sheet, Edition 2.

23. Sika, (2009) " Sika Warp®- 230C Woven carbon fiber fabric for structural strengthening", Technical Data Sheet.

24. Aslan FRP 200/201 specifications, Web site: www.aslanpacific.com.hk

25. Karlsson and Sorensen, (2007), "SIMULIA (2007) ABAQUS analysis and theory manual", Inc, Providence.

26. Witwit, J. and Alwash N., (2015) “Behavior of R/C Portal Frames Strengthened by CFRP Products” Department of Civil Engineering, College of Engineering, University of Babylon Iraq, Babylon.

27. Basim, S., Hejazi, F. and Rashid, R.S.B.M. (2019), "Embedded carbon fiber-reinforced polymer rod in reinforced concrete frame and ultra-high-performance concrete frame joints". International Journal of Advanced Structural Engineering (2019) 11 (Suppl 1), 35–51. https://doi.org/10.1007/s40091-019-00253-7